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Simulated Global Atmospheric Dust Distribution: Sensitivity to Regional Topography, Geomorphology, and Hydrology

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Introduction

Explaining the observed spatial heterogeneity of global dust emissions is important for understanding the relative role of natural and anthropogenic processes in the present day dust emissions, and thus for predicting future trends in dust production. We identify three related geomorphologic and hydrologic constraints which may contribute to this heterogeneity. Using the global Dust Entrainment and Deposition (DEAD) model (Zender et al., 2002), we investigate the implications of each process relative to a control simulation with no imposed spatial heterogeneity. We show that Aeolian erosion appears linked to regional surface geomorphology and runoff on large spatial scales.

Satellite observations show that persistent maxima in the observed mineral aerosol distribution are associated with topographic basins where loose alluvial sediments may accumulate (Prospero et al., 2002). These sediments may be responsible for greater dust emission efficiencies (i.e., erodibility) than otherwise comparable locations which lack hydrologically disturbed/renewed sediments. Dust models which attempt to account for sediment-rich source regions succeed in reproducing significant spatial features of the dust distribution (Ginoux et al., 2001; Zender et al., 2002). However, the extent to which parameterizations of source efficiency are required to explain the observed dust record, and the physical basis of such parameterizations, have not yet been adequately investigated.

Dust emissions are directly related to wind speed, atmospheric stability, surface roughness, vegetative cover, gross soil texture, and soil moisture. In addition, emissions show large variations attributable to other soil characteristics such as parent soil (saltator) texture, fine particle aggregation, soil modulus of rupture, and degree of disturbance. The second group of properties are related to current and past hydrologic activity because precipitation and surface runoff in and upstream of dust sources are linked to local soil abundance, size, chemical properties, and disturbance history.

We quantify the dust source efficiency S as the ratio of actual vertical dust mass flux F_d to the mass flux $F_{d,0}$ mobilized from an idealized surface in the absence of regional geographic influences. Thus S is intended to represent the influence of regional topography, geomorphology, and hydrology on dust emissions. If regional geomorphologic and hydrologic processes are unimportant in explaining present day dust emissions, then global simulations using $S = 1$ should perform no worse than simulations which account for regional heterogeneity.

Methods

Four one-year global dust simulations are performed, a control and three experiments. In the control simulation, called “Unity”, regional geographic properties are neglected so that $S = 1$ globally. The first experiment, called “Topo”, tests the influence of topographic basins using the

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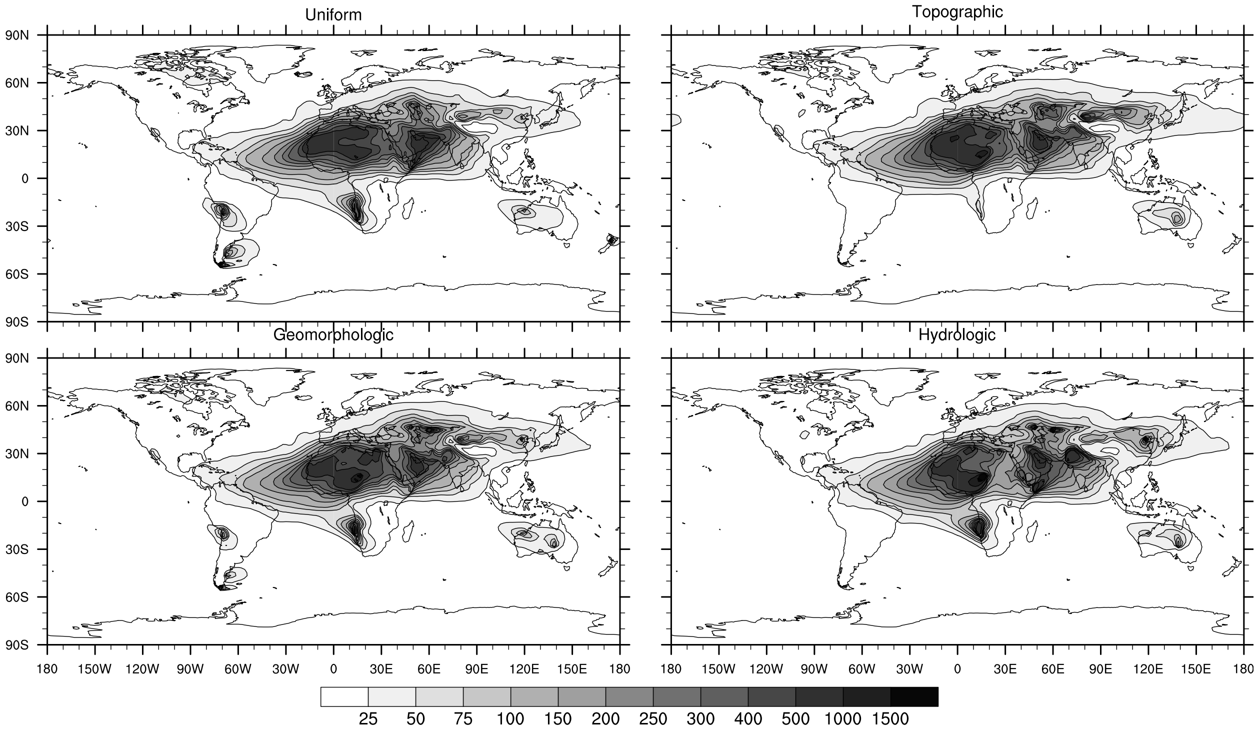

Figure 1: Predicted annual mean dust burden (mg m^{-2}) for (a) Uniform source efficiency S, (b) Topographic basins, (c) Geomorphologic basins, (d) Hydrologic basins, present day runoff.

so-called basin factor of Ginoux et al. (2001). Ginoux et al. parameterized S as the fifth power of the ratio of the local height above a regional minimum height to the total elevation range of the surrounding $10° \times 10°$ region. The second experiment, called "Geo" defines S proportional to geomorphologic basin area. The basin area is the upstream area from which surface runoff may reach a given location. We computed the basin area from a Digital Elevation Map using standard hydrologic techniques. The third experiment, called "Hydro", defines S proportional the surface hydrologic flow accumulation through each point. In this case, surface runoff was obtained from a 20 year present-day simulation of the Community Land Model.

We evaluate the importance and efficacy of each process in the DEAD model (Zender et al., 2002) forced by interpolated 6-hourly NCEP winds for the years 1994–1996. The four three-year simulations were tuned a posteriori to produce identical annual mean atmospheric mass burdens. Thus differences in the statistics of the dust distribution are due to the spatial distribution of sources, and to regional differences in the efficiency of sink processes, especially wet deposition.

Results

Figure 1 shows the annual mean dust burden simulated using four different source emission factors. The experiments show many features which are controlled by regional geomorphologic influences. All three experiments show enhanced emissions from the Bodele depression that are seen in observations (Prospero et al., 2002) but missing from the control. This regional behavior is consistent with the hypothesis that hydrologic basins are richer in dust source materials, and thus more efficient dust sources than nearby regions with comparable meteorology but less erodible source material. All experiments improve overestimated emissions near the Indian Ocean, but the Hydrologic experiment overestimates emissions in the Himalayan region.

The differences between the topographic basin experiment and the control simulation show the important impact that topography has on emissions. Assigning enhanced erodibility to topographic minima (Ginoux et al., 2001) realistically increases emissions in the central Sahara around the Bodele depression, in the Tarim Basin in eastern China, in the Aral Sea region, and in the Lake Eyre region in central Australia. Emissions are reduced in the eastern Sahara near Sudan, in Namibia, in South America near Patagonia, and in western Australia.

The differences between topographic basins and geomorphologic basins show the impact of realistically defined basins. The geomorphologic basins enhance emissions from the Namibian regions and reduce emissions from the Algerian regions of the western Sahara. These changes significantly improve model agreement with station observations of dust concentration and seasonal cycle obtained from the Rosenstiel School of Marine and Atmospheric Sciences aerosol network (not shown). Of the four erodibility assumptions tested, the geomorphologic basins produced the closest overall agreement with observations.

The differences between geomorphologic basins and hydrologic basins show the regions in which present day hydrological transport and disturbances would be expected to have the greatest impact. Regions with increased emissions include east China, the Indus River valley in Pakistan, and the Mesopotamian region in Iraq. Each of these regions has a high concentration of sediments from the upstream regions it drains. The S in active river valleys are much larger than S in desert basins, so it is somewhat surprising that the simulated dust distribution is not completely dominated by Earth's major coastal estuaries in this case. This is because other constraints in the dust model (Zender et al., 2002), primarily vegetation and soil moisture, control dust emissions in these wet regions.

Regions where present day hydrology decreases emissions include the Aral Sea region, the eastern Sahara, and Patagonia. These regions are known dust sources, and whether the present day hydrologic source/disturbance hypothesis improves model performance there should be examined using in situ or satellite observations. We note that basing erodibility on present day hydrology does not test the alternate hypothesis that present day erodibility is controlled by sediments accumulated in past climates when runoff differed. Indeed, our future work will include testing the hypothesis that present day emissions from Africa are from deposits accumulated during the moister Saharan climate of the mid-Holocene.

Table 1 compares the annual mean dust budget of the control to the three experiments. The Geo and Hydro experiments have $\sim 20\%$ shorter turnover times than Topo because their emission regions are closer to regions where wet deposition is significant.

Conclusions

Global simulations which account for regional geomorphological and hydrological influences show significant spatial distinctions from simulations which do not impose spatial heterogeneity in dust source efficiency. In many cases the signature of regional geomorphologic and hydrologic influences improves the dust simulations relative to observations. However, the model only parameterizes natural processes relevant to sediment accumulation and disturbance. Dust observations, on the other hand, record anthropogenic contributions (e.g., disturbance) to source efficiency S. The present work is a first step toward partitioning observed source enhancement between natural

Table 1: **Climatological Budget Statistics**

Quantity	Unity	Topo	Geo	Hydro
Burden[a]	22.7	22.7	22.7	22.7
Emission[b]	2066	1718	2070	2654
Lifetime[c]	4.0	4.8	4.2	4.2
τ Global[d]	0.036	0.037	0.037	0.037

[a]Prescribed atmospheric burden in Tg
[b]Emissions of $D < 10$ μm particles in Tg yr^{-1}
[c]Turnover time in days
[d]Optical depth at 0.63 μm

and anthropogenic factors.

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